JUNE 3RD, 2020, EEMS033

CAV 7A.3.1.1 CAR CACC OPERATIONAL ENERGY CONSUMPTION TEST AT INTERSECTION WITH ACTIVE TRAFFIC SIGNAL CONTROL

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VEHICLE TECHNOLOGIES OFFICE ANNUAL MERIT REVIEW JUNE 1-3, 2020

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Energy Efficient Mobility Systems (EEMS)
Vehicle Technologies Office
U.S. Department of Energy

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OVERVIEW

- **Timeline**
  - **Project start date:** Jan 1 2017
  - **Project end date:** Aug 31 2020
- **Budget**
  - **Total project funding: $1075K**
    - **100% DOE/VTO**
  - **Funding for FY 2017: $493K**
    - **LBL: $407K**
    - **NREL: $86K**
  - **Funding for FY 2018: $355K**
    - **LBL: $269K**
    - **NREL: $86K**
  - **Funding for FY 2019: $225K**
    - **LBL: $75K**
    - **NREL: $150K**

- **Barriers**
  - **Energy consumption evaluation in freeway and arterial corridor traffic level with different CAV market penetrations**
  - **How to operate signalized intersection with CAVs for energy saving**
  - **How to manage mixed traffic with low CAV market penetrations for mobility improvement and energy saving**
- **Collaboration**
  - **LBNL (project lead)**
  - **NREL**
  - **UC Berkeley**
  - **Output to EEMS031, micro simulation**

RELEVANCE & OBJECTIVES

- **Objectives: Investigate CAVs (such as CACC - Cooperative Adaptive Cruise Control) and real-time simulation for operation to study impact on energy use at a signalized intersection with Active Traffic Signal Control (ATSC)**

- **Active Traffic Signal Control and coordination with CAVs at a signalized intersection could reduce energy consumption**
- **Test data will be useful for modeling of CAV movement at arterial intersections for microscopic simulation which could be used for**
  - **Energy consumption evaluation in operation level**
  - **Simulated data in operation level could be used to calibrate Parameterized Fundamental Diagram; the latter can be used for CAV modeling and simulation in meso-macro level**

MILESTONES

- **Rescope in March 2020: changed CAV use from CACC trucks to CACC cars due to low speed control problem for the CACC trucks – support from Volvo delayed due to COVID-19.**

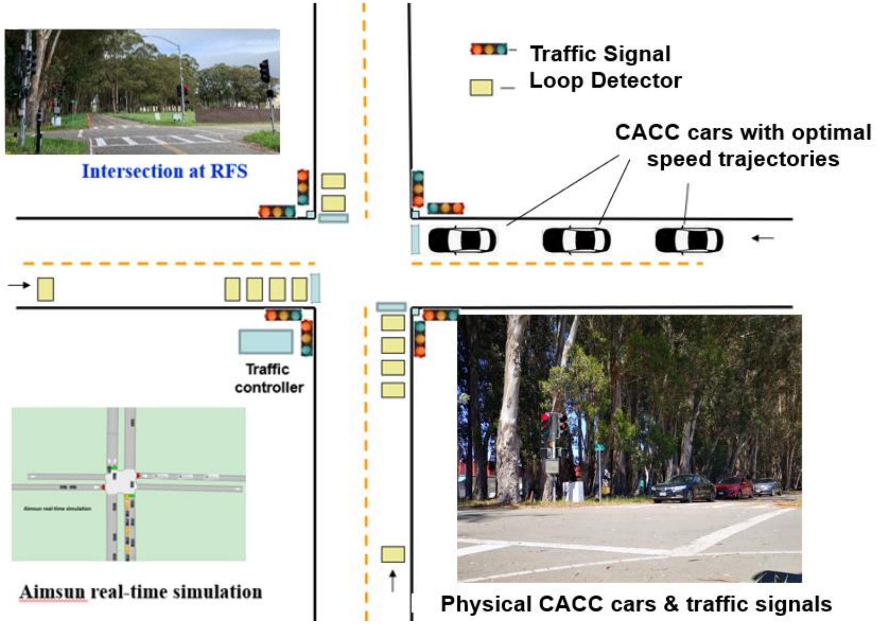
Milestone Name/Description	Criteria	End Date
Q2: 3-Truck CACC operational test data at intersection with Active Traffic Signal Control (LBNL)	Q2: Test data available including: real-time simulation data, truck data, and traffic signal data	6/30/2019 delayed
Q4: Test data analysis results on energy saving for CACC truck operation at signalized intersection (LBNL)	Q4: Data analysis results for CACC truck intersection operation with Active Traffic Signal Control	9/30/2019 delayed
Q4: CACC truck air-flow test data analysis results; the data was obtained at Transport Canada Test Track (NREL)	Q4: Report on data analysis results of air-flow effect on aerodynamic drag and engine temperature	9/30/2019 delayed
Q4: Modeling of fuel consumption for 2014 Volvo VNL475 truck model based on field test using year 2001 Freightliner N-14 trucks	Q4: Fuel consumption mapping between 2014 Volvo VNL truck and 2001 Freightliner N-14 truck	9/30/2019 delayed

APPROACH

- Extend CACC capabilities of three passenger cars with different powertrains
- Developing real-time simulation with 3-CACC cars imbedded
- Using real-time simulation for Active Traffic Signal Control (ATSC)
- ATSC Algorithm is to directly maximize the intersection overall throughput and minimize the Total Delays
  - ➔ indirectly reduce energy consumption
    - ➔ to generate speed trajectory for CACC cars
- All parts are connected with V2V and V2I and synchronized
- Whole process repeating for multiple times
- CAN-Bus fuel rate to be used for energy consumption evaluation
- Comparing with baseline case with Actuated Traffic Signal Control without integration with CACC cars

CONCEPT OF OPERATIONS

- Concept of Operation: Integrated & synchronized with V2I and V2V
  - Input to CACC cars: virtual front vehicles speed and distance, signal timing, advisory speed
  - Real-time simulation with CAV movement imbedded D2I
  - ATSC using simulated traffic to determine Green Distribution
  - Evaluate mobility and energy consumption in simulation
  - Using air fuel ratio from the CAN to evaluate actual fuel consumption on cars
  - RFS – Richmond Field Station, a Berkeley Research Campus
  - Aimsun – micro traffic simulation package



Overall system synchronized and integrated with V2V and V2I DSRC

U.S. DEPARTMENT OF ENERGY SMARTMOBILITY Systems and Modeling for Accelerated Research in Transportation

Signal control algorithm—a dynamic programming method

- Objective: maximize throughput
- Throughput: $Q_j = \sum_{i=1}^{N} D_j$ - Total number of vehicles involved
  - where j is stage (phase) ID; i is the number of intersection approaches; D_j is the number of departure vehicles
- Performance function (total throughput of the current stage and previous stages): $v_j = v_{j-1} + Q_j$
- Identify the optimal signal phase sequence, signal timing and number of stages that **maximizes the performance function** over a control horizon
- The cycle length varies based on the optimal signal timing and stage numbers

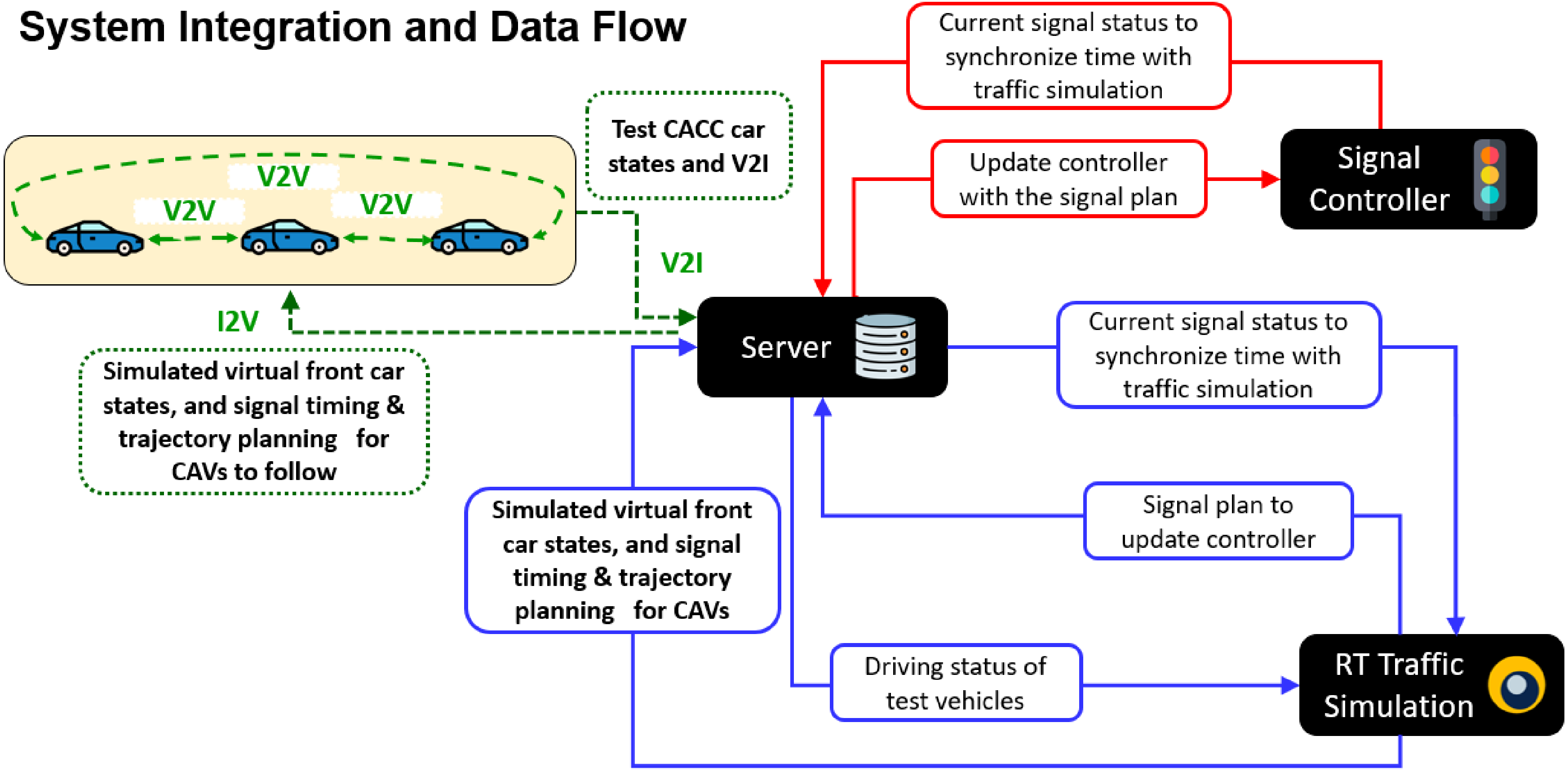
REAL-TIME ATSC SIMULATION WITH CAVS

Proposed signal control algorithm with trajectory planning

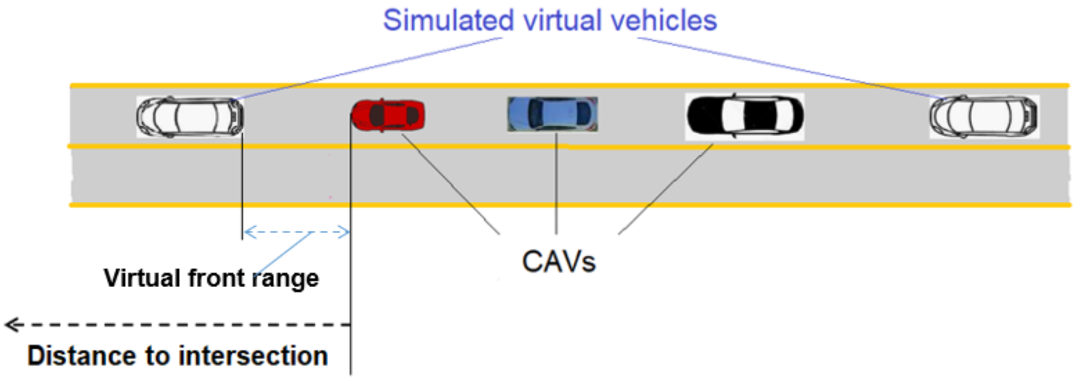
- **Flexible cycle length**, adaptive to demand variations
- **Simple algorithm**, relies on predictions of two vehicle states: pass without slow down and pass after joining the queue
- **Fast search for optimal solutions**: using parallel computing with dynamic programming and taking advantage of the monotonic value function
- Incorporate **trajectory planning** with signal optimization
- Feasible for **mixed traffic conditions**
- Adopted new algorithms developed under CAV Task 1.2, different from what we developed and simulated under this project in FY 2019.

SYSTEM INTEGRATION

System Integration and Data Flow



SYSTEM INTEGRATION AND TEST



Physical CACC cars and traffic signals

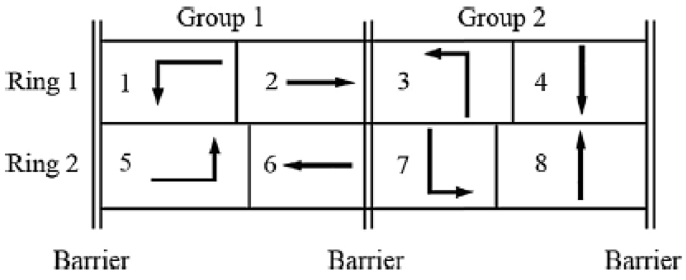
Wireless linked control cabinet and 2070 controller

REAL-TIME SIMULATION RESULTS

Real-time simulation outputs

- **Sample energy and mobility outputs:**
  - **Aggregated data for small sections in a road network**
  - **A long road link can be divided into multiple sections**
  - **Temporal resolution of the sample data: 180 s**
  - **Spatial resolution of the sample data: 200 m**
  - **Speed estimation: VMT / VHT**

Phase #	Time (s)	Link ID	Section Length (m)	Fuel by MOVES (Gal)	VMT	VHT	Fuel by VT (Gal)
1	180	6200	200	0.136499	5748.59	615.8	0.108848
2	180	6200	400	0.12899	4501.95	695.7	0.119069
3	180	6200	600	0.0855459	3529.89	390.2	0.0693433
4	180	6220	200	0.138058	5237.9	682.9	0.118451
5	180	6220	400	0.0998195	3356.7	546.1	0.0937738
6	180	9166	200	0.186466	7572.37	844.2	0.780294
7	180	9166	400	0.161858	6469.72	714.1	0.133109
8	180	9166	600	0.177512	5806.07	826.8	0.148878



NEMA Phase Definition

NEMA: National Electrical Manufacturers Association

REAL-TIME SIMULATION RESULTS

Real-time simulation outputs

- **Signal control outputs:**
  - **Designed for NEMA 8-phase controller**
  - **The table shows a signal controller without dedicated left-turn arrows**
  - **Cycle start time is measured from the beginning of a test**

Cycle Start Time (s)	Cycle Length (s)	P1 GT (s)	P2 GT (s)	P3 GT (s)	P4 GT (s)	P5 GT (s)	P6 GT (s)	P7 GT (s)	P8 GT (s)	Y (s)	AR (s)
116.1	43	0	9	0	24	0	9	0	24	3	2
159.1	61	0	15	0	36	0	15	0	36	3	2
515.1	43	0	18	0	15	0	18	0	15	3	2
558.1	46	0	18	0	18	0	18	0	18	3	2
604.1	46	0	12	0	24	0	12	0	24	3	2
1798.1	64	0	21	0	33	0	21	0	33	3	2
1862.1	64	0	18	0	36	0	18	0	36	3	2

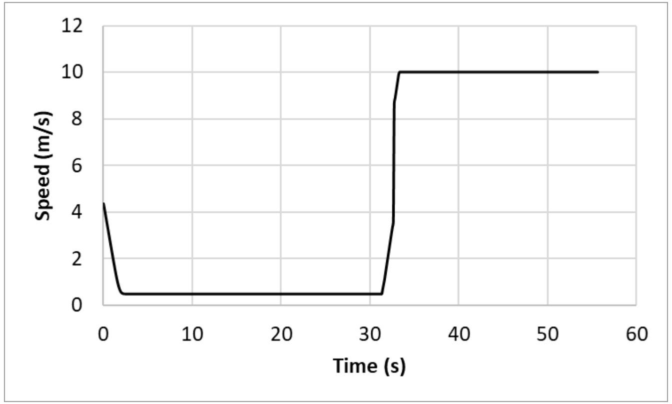
- P1 – P8: Phase 1 to Phase 8
- GT: green time
- Y: yellow time
- AR: all red time

REAL-TIME SIMULATION RESULTS

Real-time simulation outputs

- **Vehicle trajectory:**
  - **Detailed vehicle position and speed**
  - **Data collected at 10 HZ**
  - **Can be imported to more detailed energy models such as Autonomie**

Time (s)	Vehicle ID	Link ID	Position in Link (m)	Speed (m/s)
113.3	17	9205	135.324	4.35088
113.4	17	9205	135.747	4.09824
113.5	17	9205	136.144	3.8456
113.6	17	9205	136.516	3.59295
113.7	17	9205	136.862	3.34031
113.8	17	9205	137.184	3.08766



A sample vehicle trajectory with trajectory planning that prevents complete stop during the red light

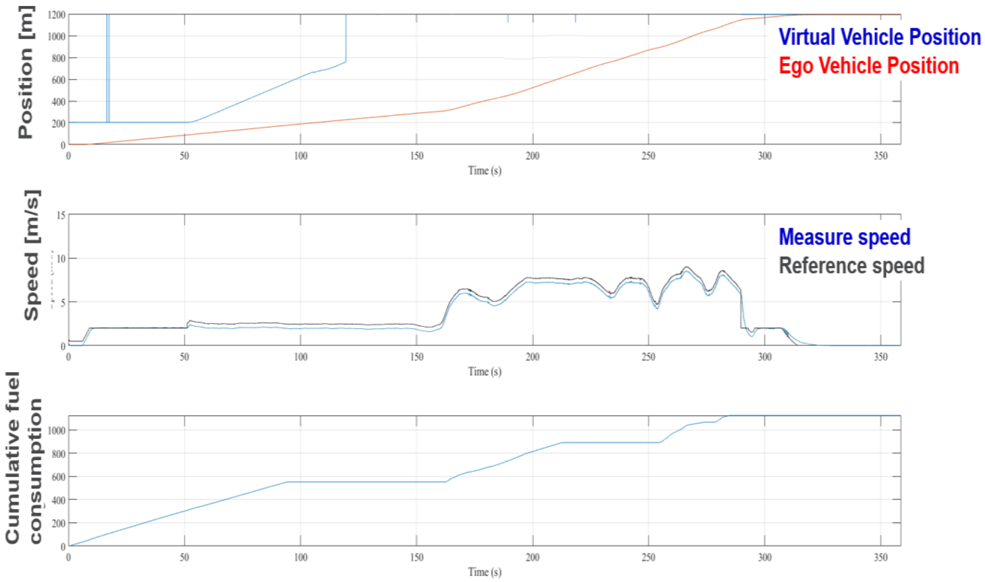
SYSTEM INTEGRATION AND TEST

No Speed Reduction at Green Light

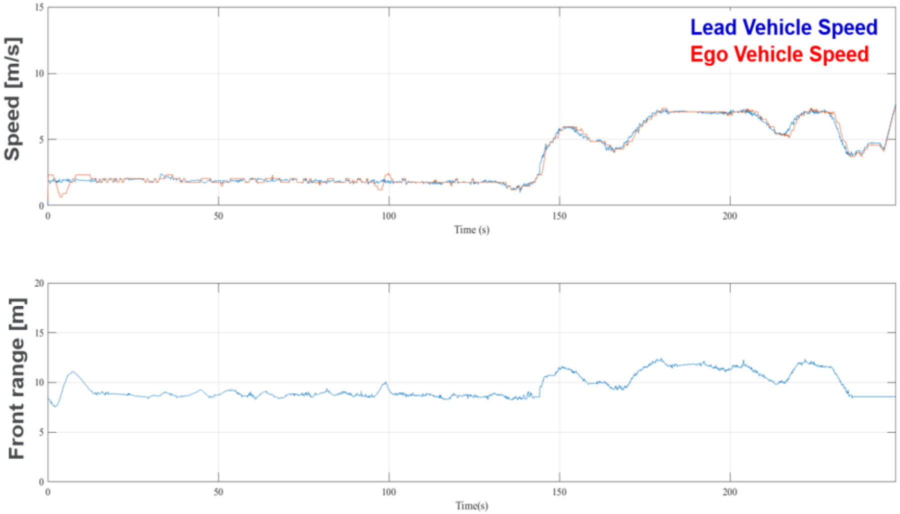
Speed Reduction at Green Light due to Virtual Vehicle

SYSTEM INTEGRATION AND TEST

Lead ACC Car: Position with respect the origin in a ground coordinate system, which can be used to determine Distance to Intersection (D2I); Speed and Cumulated Fuel Consumption



Follower- CACC Car, speed and front range (distance)



RESPONSES TO PREVIOUS YEAR COMMENTS

- The reviewer said that DSRC is not an established communication protocol. The arguments still go on for 5.9 versus DSRC. Both protocols should be established for the project.
  - Ans: we use 5.9 GHz DSRC, but OBU and RSU have different protocol; both are used
- it would be helpful if the PI were to provide some narration explaining the key parts of the simulation and highlight where the reviewers should focus attention to make the simulation more useful and understandable.
  - Ans: we put in more details this year
- The project lagged behind
  - Ans: Delay due to late contract and truck low speed control hurdle until changed to cars
- It was not fully clear to the reviewer how the DOT project and this one were specifically related
  - This project was to use the CACC capable trucks developed under DOT EAR Program
- This could even be a good place for an industry group to have been involved, such as SAE and the Technology Maintenance Council (TMC).
  - Ans: we could link with them in the future.

RESPONSES TO PREVIOUS YEAR COMMENTS

- it seemed to the reviewer that the benefit of using trucks in ACC in urban environments to help with congestion is not too practical.
  - Ans: Agreed. ACC and CACC alone cannot significantly improve urban traffic; In fact, ACC will make traffic worse; their operation must be integrated with Active Traffic Control (ACM) for freeways and Active Traffic Signal Control (ACTS) in arterial corridors with V2V & V2I.
- The reviewer was not confident that the funding left is sufficient for this project team to complete the research work left.
  - Ans: Yes. We should be able to use the remaining funds to accomplish what we proposed before.
- The work conducted in this project could be very useful for industry although it does not bring ideas beyond the current research program conducted in universities and industry.
  - Ans: Agreed. We will need to move towards application in coalition with industry. Start some projects with ACM (American Center for Mobility) would be steps in this direction.

REMAINING CHALLENGES

- To quantify fuel saving benefit for Prius and Accord through OBD II interface
- To improve traffic signal timing on CAVs to reduce delays
- Optimal trajectory planning on the server not implemented yet
- Green distribution cannot be completely determined well in advance for CAV to plan the speed trajectories
- To handle grey area problems: green extension, yellow extension, red-light run; traffic prediction for all phases/movements
- To conduct system tuning with 3 CAVs integrated
- To conduct extensive tests for mobility and energy consumption evaluation
- The above works are expected to be accomplished before August 31 2020 (3 months after the shelter-in-place is lifted)

PROPOSED FUTURE WORK BEYOND THIS PROJECT

- **Real-time simulation with Hardware-in-the-Loop (HIL) to create a nearly realistic mixed traffic environment for CAV tests for mobility and energy consumption evaluation**
  - **CACC Trucks and passenger cars with different powertrains**
    - **On Arterial corridor with multiple intersections with Active Traffic Signal Control**
    - **On Freeway corridor with Active Traffic Management (ACM)**
  - **Combined with American Center for Mobility (ACM) test projects**
- **Fuel consumption tests for 3 CACC cars with different powertrains on test track**
- **Combined Fuel consumption and emission tests for 3-truck CACC operation along a freeway corridor (or for long distance freight movement operation) with real-world traffic and professional truck drivers**
- **Any proposed future work is subject to change based on funding levels**

SUMMARY

- Developed feasible Concept of Operations
- Developed real-time simulation which can imbed the CAVs' movement and with flexible levels of CAVs
- Developed Active Traffic Signal Control (ATSC) Algorithm to incorporate CAVs simulation for direct traffic improvement, and indirect energy saving
- Adopted new algorithms developed under CAV Task 1.2, different from what we developed under this project in 2019
- Developed DSRC packets for integration of the system using RSU (Roadside Units) to cover test track with movement and preliminarily tested
- CACC car localization with onboard sensor and GPS to determine D2I
- Synchronized the overall system and Integrated with two CACC passenger cars
- Quantified fuel saving benefit for CACC capable Honda According with fuel rate
- Quantified fuel saving benefit in the real-time simulation with MOVES
- Conducted initial test

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MOBILITY FOR OPPORTUNITY

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TECHNICAL BACK-UP SLIDES

PUBLICATION AND PRESENTATION

- X. Y. Lu, S. Shladover, and S. Bergquist, Truck CACC implementation and test to verify control performance, Transportation Research Record, 2019, sagepub.com/journals-permissions, DOI: 10.1177/0361198119842122, journals.sagepub.com/home/trr
- X. Y. Lu, and S. E. Shladover, B. McAuliffe, S. Bergquist and A. Kailas, New 3-Truck CACC Field Test for Fuel Consumption and Control Performance, Automated Vehicle Symposium, San Francisco, July 2018
- Liu, H., Lu, X. Y., & Shladover, S. E. (2019). Traffic signal control by leveraging Cooperative Adaptive Cruise Control (CACC) vehicle platooning capabilities. Trans. Research Part C: Emerging Technologies, 104, 390-407
- H. Liu, X. Y. Lu, and S. E. Shladover, Traffic Signal Cooperation for Enhancing Cooperative Adaptive Cruise Control (CACC) Vehicle String Operations, Journal of TRB, Transportation Research Record, to appear

REAL-TIME ATSC SIMULATION WITH CAVS

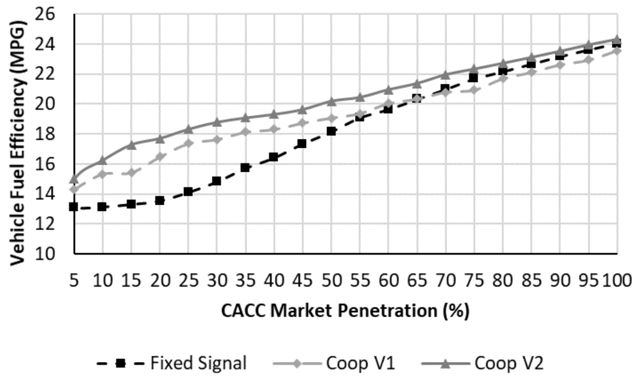
Vehicle trajectory planning

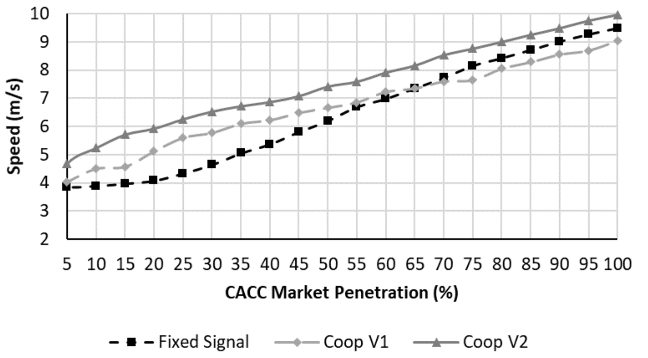
- Guide the subject vehicle to pass the intersection without full stop
  - Cruise at a low speed during red
  - Join the end of the queue just as the signal turns green
- Reduce energy loss by **eliminating stops in queue**
- Increase intersection throughput by **increasing vehicle speed** when they pass the stop bar
- Only applies to the platoon leaders
  - Only used as a reference speed by CAVs
  - Algorithm deactivates when the queue length changes (cut-in handling)

SIMULATION RESULTS

Results (trajectory planning turned off)

- Evaluate the benefit obtained from the signal control optimization only
- Both cooperative algorithms outperform the baseline case at low and median CACC market penetrations
- The benefits become smaller at higher CACC market penetrations

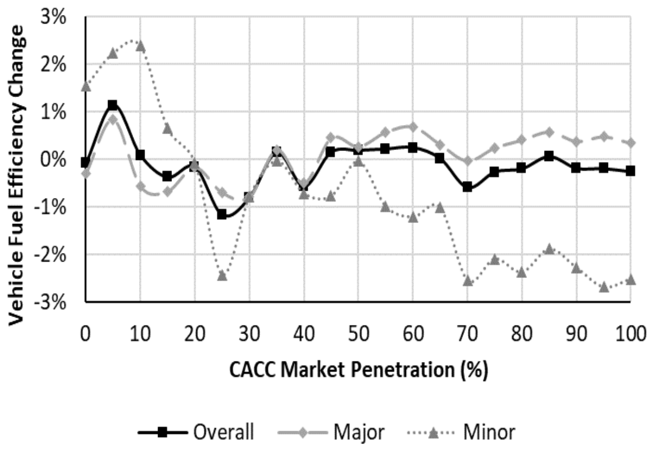




SIMULATION RESULTS

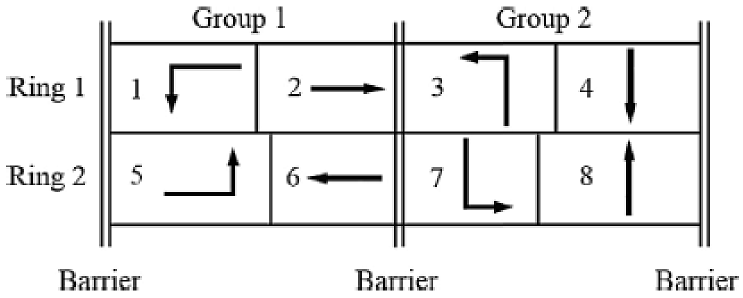
Performance when the trajectory planning is turned on

- The overall benefit of trajectory planning is small
- The algorithm is deactivated frequently due to cut-ins
- There are uncertainties in predicting when the queue starts to move, especially if the queue contains mixed traffic
- It makes the subject vehicle stop when it joins the queue but the queue has not yet started moving
- This removes the energy benefit



SIGNAL COOPERATION FOR CACC VEHICLE STRINGS

- **Constraints:**
  - $\sum_{j=1}^{4}(g_j + t_{YR}) = C$
  - $\sum_{j=5}^{8}(g_j + t_{YR}) = C$
  - $\sum_{j=1}^{2}(g_j + t_{YR}) = \sum_{j=5}^{6}(g_j + t_{YR})$
  - $\sum_{j=3}^{4}(g_j + t_{YR}) = \sum_{j=7}^{8}(g_j + t_{YR})$

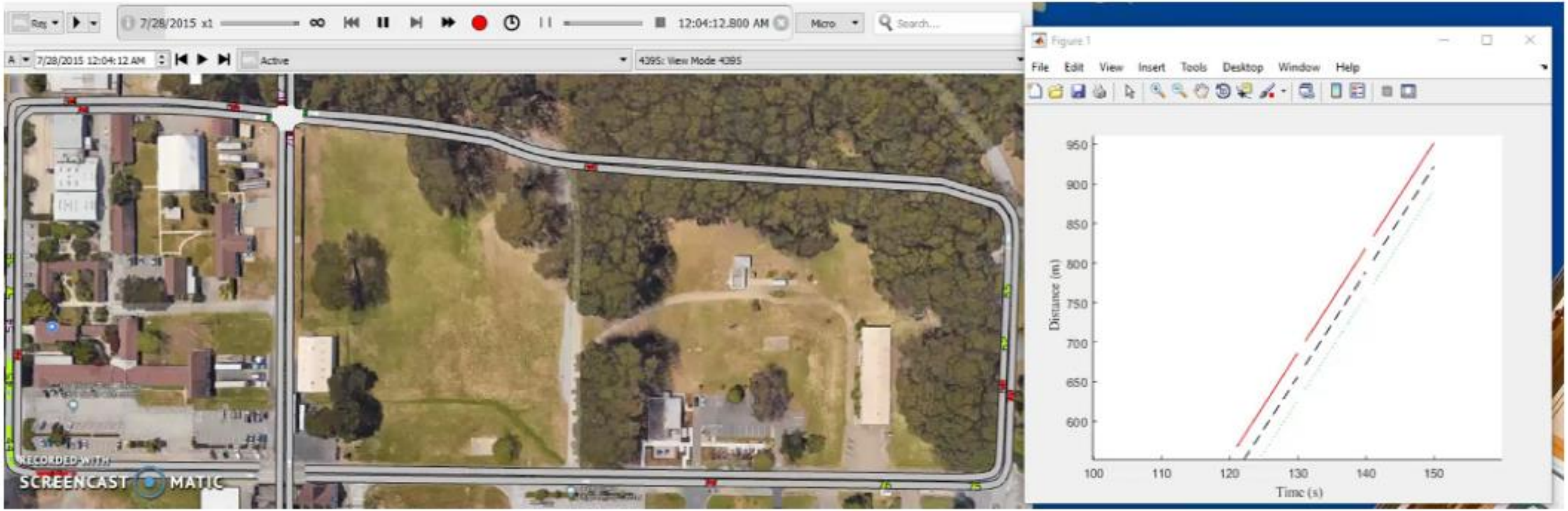


Remark:

- **1st and 2nd constraints: cycle length constraints.**
- **3rd and 4th constraints state that the green time of the two rings in a group should be the same.**

HARDWARE-IN-THE-LOOP SIMULATION

- Simulation in FY 2019



Red: CACC string leader
Green: CACC string follower

3 vehicle real-time running distance trajectory